Strategies for adapting maize to climate change and extreme temperatures in Andalusia, Spain

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ABSTRACT: Climate projections indicate that rising temperatures will affect summer crops in the southern Iberian Peninsula. The aim of this study was to obtain projections of the impacts of rising temperatures, and of higher frequency of extreme events on irrigated maize, and to evaluate some adaptation strategies. The study was conducted at several locations in Andalusia using the CERES-Maize crop model, previously calibrated/validated with local experimental datasets. The simulated climate consisted of projections from regional climate models from the ENSEMBLES project; these were corrected for daily temperature and precipitation with regard to the E-OBS observational dataset. These bias-corrected projections were used with the CERES-Maize model to generate future impacts. Crop model results showed a decrease in maize yield by the end of the 21st century from 6 to 20%, a decrease of up to 25% in irrigation water requirements, and an increase in irrigation water productivity of up to 22%, due to earlier maturity dates and stomatal closure caused by CO_2 increase. When adaptation strategies combining earlier sowing dates and cultivar changes were considered, impacts were compensated, and maize yield increased up to 14%, compared with the baseline period (1981–2010), with similar reductions in crop irrigation water requirements. Effects of extreme maximum temperatures rose to 40% at the end of the 21st century, compared with the baseline. Adaptation resulted in an overall reduction in extreme T_{max} damages in all locations, with the exception of Granada, where losses were limited to 8%.

KEY WORDS: Climate change · Impact · Adaptation · Maize · Crop model · Regional climate model · Extreme temperature

1. INTRODUCTION

The effects of climate change on agriculture in Europe have been studied at both continental (Olesen & Bindi 2002, Bindi & Olesen 2011, Christensen et al. 2012) and regional scales, focusing on e.g. the Mediterranean basin or the Iberian Peninsula (IP) (Mínguez et al. 2007, Ruiz-Ramos & Mínguez 2010, Garrido et al. 2011). The projected increase in temperature, the changes in the pattern of rainfall, and their interactions with increasing CO_2 concentrations would cause variable effects on harvests depending on location, growing season, crop, and variety. For example, projections for southern Spain show a higher rise of spring and summer temperatures, compared with other seasons and regions of IP (Christensen & Christensen 2007, López de la Franca et al. 2013). This should cause a shortening of the phenological cycle that would offset the enhanced photosynthetic rates under increased CO_2. The final result of these counteracting effects would be a decrease in yield and biomass for irrigated summer crops in southern Spain (Guereña et al. 2001, Mínguez et al. 2007, Giannakopoulos et al. 2009, Garrido et al. 2011).

Most impact assessment studies in agriculture use crop models in combination with climate scenarios (Meza et al. 2008, Moriondo et al. 2010, Vučetić 2011). The climate scenarios are usually provided by general climate models (GCMs) downscaled by either statistical (Wilby et al. 1998) or dynamical (Castro et al. 2005) techniques, or by a combination of both (Førland et al. 2011). Dynamical downscaling is done by using regional climate models (RCMs) that generate projections (Giorgi et al. 2001) at a compatible resolution with the assessment of regional and local impacts. RCMs are especially useful in regions of complex orography, as is the case for IP (Guereña et al. 2001).

Climate projections contain multiple sources of uncertainty, such as selection of emission scenarios and model-dependent uncertainty, e.g. parameterization and resolution (Olesen et al. 2007, Ruiz-Ramos & Mínguez 2010, Osborne et al. 2013). RCM simulations may present large biases when compared to observations (Dosio & Paruolo 2011, Ceglar & Kajfež-Bogataj 2012), which can limit their application for local/regional assessment. For that reason, the current methodology includes the use of ensembles of climate projections (Christensen et al. 2009, Semenov & Stratonovitch 2010), and evaluation using local climate data.

Climate change will strongly increase the frequency and intensity of extreme events (Easterling et al. 2000, Sánchez et al. 2004, Beniston et al. 2007), similar to the case of extreme maximum temperature (T_{max}) events (Beniston 2004, Meehl & Tebaldi 2004, Schär & Jendritzky 2004, Tebaldi et al. 2006, Beniston et al. 2007, Hertig et al. 2010). These episodes have a direct influence on crops and therefore should be considered in a comprehensive impact assessment (García-López et al. 2014). For example, T_{max} events have been reported as the most hazardous events for maize under irrigated conditions in Andalusia, since high temperatures during flowering and grain-filling are expected to result in lower grain yield (Herrero & Johnson 1980, Ruiz-Ramos et al. 2011).

Although some studies address the adaptation of irrigated crops to climate change (Garrido et al. 2011, Olesen et al. 2011, Moradi et al. 2013), or the effect of extreme events (Ruiz-Ramos et al. 2011), few have evaluated adaptations in relation to those extreme events (Travis & Huisenga 2013, Trnka et al. 2014). In fact, the current ecophysiological crop models do not simulate the whole extent of weather extremes on critical crop phases such as pollination or grain-filling (García-López et al. 2014), in turn introducing an important additional source of uncertainty in the context of climate change impact. Furthermore, crop modeling also incorporates uncertainty, due to both the model mechanisms to describe the processes, which is partially addressed by the use of several crop models, i.e. an ensemble of impact models, and the lack of local calibration (Palosuo et al. 2011, Rötter et al. 2011). For that reason, the crop model has to be calibrated with field data at the relevant spatial scale for the study to improve its application (Boote et al. 2013). Then, for a specific crop in a regional cropping system, as is the case for maize in Andalusia, an ecophysiological crop model with site-specific calibration and validation must be considered.

In Andalusia, agriculture and livestock account for 4.3% of regional gross domestic product (GDP; MAGRAMA 2015). Irrigated agriculture represents around 64% of total agricultural income, although only 32% of the area is irrigated (CAP 2011). Maize is a traditional irrigated summer crop in this region, with 81.9% (32 000 ha) of the cultivated area located in the Guadalquivir Valley (RAEA 2012). Due to the foreseen increase in temperature and reference evapotranspiration (Espadafor et al. 2011), water requirements for maize could increase in the future in this region (Mínguez et al. 2005) if adaptation strategies are not used.

Considering the importance of irrigated agriculture in Mediterranean environments, the objective of this study is to determine the effect of adaptation strategies for irrigated maize in Andalusia in terms of yield and water requirements. The adaptation strategies proposed are evaluated in relation to the impact of T_{max} as one of the most relevant extreme events for irrigated maize in Andalusia.

2. MATERIALS AND METHODS

2.1. Location

We selected 5 locations (Fig. 1) according to field experimental data availability, representing different areas of maize cultivation in Andalusia: 2 in Seville province (Alcalá del Río and Lora del Río), 2 in Córdoba province (Palma del Río and Córdoba), and 1 in Granada. The Seville and Córdoba locations are in the Guadalquivir River basin, ranging from 11 to 117 m above sea level. Granada has a greater altitude (630 m), and is close to the Sierra Nevada Mountains. The climate is Mediterranean type, with dry summers,

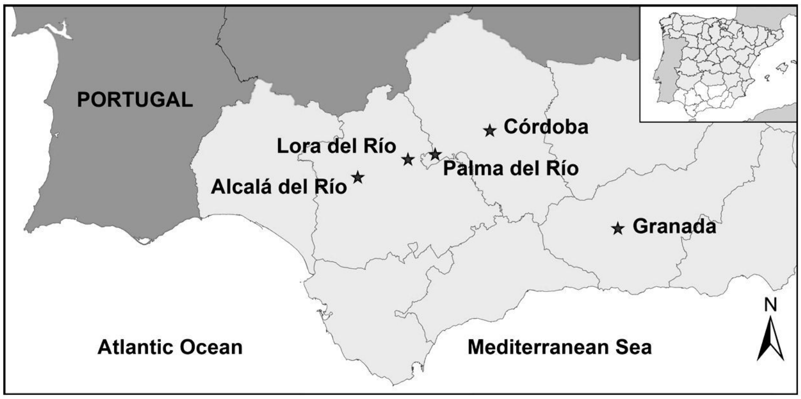

Fig. 1. Study locations, corresponding to sites with maize field experiments

at all locations, according to the Köppen classification (Essenwanger 2001). For the locations along the Guadalquivir basin, annual mean precipitation is ca. 600 mm, concentrated mainly from autumn to spring; annual mean temperature is ca. 18°C, with a T_{max} during the maize-growing season (March–August) of ca. 30°C (Table 1). Conditions are drier and cooler in Granada, with a T_{max} during the growing season (March–August) around 28°C (Table 1).

2.2. Climate data

Daily observed and simulated climate data of T_{max} and T_{min}, solar radiation, and precipitation were used. For observed climate, weather data from the Agroclimatic Information Network of Andalusia (RIA in Spanish; Gavilán et al. 2006) from 2001–2010 were used (www.juntadeandalucia.es/agriculturaypesca/ifapa/ria).

For simulated climate, data from a subset of 12 RCMs from the ENSEMBLES project (www.ensembles-eu.org) at 25 km horizontal resolution with a bias correction in temperature and precipitation (Dosio & Paruolo 2011, Dosio et al. 2012) were used. The correction was done with respect to the E-OBS gridded observational database (Haylock et al. 2008). The bias-corrected ensemble is hereafter named ENS-EOBS. Before using the simulated database as input for the crop model, it was tested for T_{max}, T_{min}, and seasonal rainfall (March–August; Table 2) against observed weather station data (from RIA). The bias correction could not be done for solar radiation (SRAD), because E-OBS does not include radiation data. The SRAD bias was small, and it ranged between 0 MJ m^{-2} d^{-1} (at Córdoba in spring) and –1.8 MJ m^{-2} d^{-1} (at Palma del Río in July). The consequences of SRAD bias on simulated yield were evaluated, and resulted in a mean error of maximum yield change, averaged over locations, of 4.3% (results not shown).

2.3. Crop modeling

We used the CERES-Maize crop model (Jones & Kiniry 1986) in the DSSAT v. 4.5 platform (Decision Support System for Agrotechnology Transfer; Jones et al. 2003, Hoogenboom et al. 2010). This is an ecophysiological model which simulates crop growth and development, and can be used with climate projections and elevated CO_2 conditions. The CERES-Maize model uses radiation use efficiency (RUE) to calculate biomass from intercepted photosynthetically active radiation (PAR) by the crop canopy. Photoassimilate partitioning and remobilization to grains determine the crop yield. Duration of phenophases, e.g. days from emergence to end of the juvenile phase, or grain-filling duration, are estimated by growing degree days (GDD; °Cd), which is the accumulated exposure to average daily temperature above a threshold (8°C) below which there is no development, and a maximum of 34°C above which the rate of development remains constant. Phenophase dura-

Table 1. Location, soil type (Soil Survey Staff 1999), annual mean temperature (T_{mean}) and accumulated precipitation (Precip) from the nearest weather stations, years with experimental data from Red Andaluza de Experimentación Agraria (RAEA), and mean observed sowing date. All locations have a Mediterranean climate according to Essenwanger's (2001) classification

Location	Coordinates	Soil type	T_{mean} (°C)	Precip (mm)	RAEA data years	Sowing date
Alcalá del Río	37.51°N, 5.96°W	Xerofluvent	18.3	597	2003, 2005, 2006, 2007	17 Mar
Lora del Río	37.64°N, 5.52°W	Xerofluvent	18.2	663	2003	20 Mar
Palma del Río	37.70°N, 5.28°W	Xerofluvent	18.2	634	2003, 2007	21 Mar
Córdoba	37.86°N, 4.79°W	Xerofluvent	17.9	661	2005, 2006, 2007, 2008, 2009, 2011	21 Mar
Granada	37.17°N, 3.63°W	Xerorthent	15	385	2005, 2006, 2007, 2008, 2009, 2010	23 Apr

Table 2. Climate data during the maize growing cycle: monthly maximum (T_{max}) and minimum (T_{min}) temperatures and accumulated precipitation for Agroclimatic Information Network of Andalusia (RIA) station data (2001–2010), and difference between mean values from these data and those from the ensemble mean (12 regional climate models) from the bias-corrected ensemble ENS-EOBS, for the baseline period 1981–2010

Location	Source	T_{max} (°C)						T_{min} (°C)						Precipitation (mm mo^{-1})					
		Mar	Apr	May	Jun	Jul	Aug	Mar	Apr	May	Jun	Jul	Aug	Mar	Apr	May	Jun	Jul	Aug
Alcalá	RIA	20.7	23.4	27.1	32.4	35.4	35.2	8.3	10.2	12.8	16.5	17.6	17.9	62	59	31	5	0	7
del Río	ENS-EOBS	−0.2	−0.4	0.0	−0.6	0.3	0.4	0.1	0.1	0.4	0.3	1.6	1.4	−14	−15	−6	6	2	−3
Lora	RIA	20.6	23.6	27.5	33.3	36.3	36.0	7.8	9.6	12.4	16.5	17.8	18.3	66	63	43	4	1	2
del Río	ENS-EOBS	−0.4	−0.8	−0.4	−1.3	−0.4	−0.1	0.2	0.4	0.7	0.3	1.4	1.1	−15	−17	−17	7	2	1
Palma	RIA	20.0	23.1	27.2	33.2	36.3	36.0	8.0	10.0	12.9	17.0	18.8	19.1	70	56	49	7	0	5
del Río	ENS-EOBS	0.0	−0.3	−0.1	−1.2	−0.3	−0.1	−0.3	−0.2	0.0	−0.3	0.4	0.2	−18	−8	−23	4	3	−3
Córdoba	RIA	19.7	22.5	26.6	32.8	36.4	36.1	7.5	9.3	12.1	16.6	18.5	19.2	89	58	40	10	3	6
	ENS-EOBS	0.1	0.1	0.4	−0.8	−0.2	−0.1	−0.2	0.1	0.5	−0.1	0.6	0.1	−39	−11	−13	−1	1	−3
Granada	RIA	18.5	21.0	25.3	32.2	35.4	34.8	4.7	6.5	9.7	14.3	16.1	16.1	50	38	31	4	0	3
	ENS-EOBS	−1.4	−1.3	−1.0	−2.3	−0.9	−0.6	1.1	1.4	1.6	1.1	2.4	2.6	0	5	2	17	10	4

tion, in days, correlates to average temperature, except for the duration of flower induction, which is controlled by day length (Kiniry 1991). CO_2 enrichment affects dry matter production and transpiration. Potential growth rate is affected by a multiplicative coefficient, increasing the daily dry matter production at optimum temperature, water, and nitrogen supply (Kimball 1983, Cure & Acock 1986). This coefficient is 1.17 for C3 crops and 1.05 for C4 crops when [CO_2] is 550 mg l^{-1}. Also, transpiration rate is affected by stomatal resistance, which increases with CO_2 concentration (Hoogenboom et al. 1995).

Model inputs include 6 cultivar-specific parameters, daily meteorological variables (maximum and minimum temperatures, solar radiation, precipitation, wind run, and relative humidity), soil features (depth, texture by layers, water holding capacity), and crop management (sowing date, population density, fertilization, and irrigation, among others). Cultivar parameters, controlling phenology, growth, and grain yield, have to be set during the calibration process.

Soil and crop experimental data for crop model calibration and validation were taken from the Andalusia Network of Agricultural Trials (Red Andaluza de Experimentación Agraria, or RAEA; www.juntadeandalucia.es/agriculturaypesca/ifapa/web/ifapa/productos/transferencia). The data corresponded to field experiments with the HELEN cultivar (FAO 700), from 2003 to 2011 (Table 1). Omitted years were due to insufficient weather data or agronomic causes not simulated by the crop model, such as pests and diseases preventing adequate crop growth. Sowing dates were in March for sites in the Guadalquivir basin, and in April for Granada (Table 1). Target population densities of 10 plants m^{-2} were sown in rows 0.75 m apart, and arranged in a randomized block design. Fertilizer and irrigation management was always set to avoid nutrient and water limitations.

Crop measurements included sowing, emergence, silking, and harvest dates, plant population at emergence, grain weight, and yield. Maturity dates were estimated from Iglesias & Mínguez (1995). The experiments used for calibration were from Granada (years 2005, 2006, and 2007), while the other locations were used for validation, as were some years from Granada (2008, 2009, and 2010). Calibration and validation were evaluated in terms of root mean square error (RMSE) and mean bias error (MBE) between observed and simulated data:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_i^n (S_i - O_i)^2}{n}} \quad (1)$$

$$\mathrm{MBE} = n^{-1} \sum_{i=1}^{N} (S_i - O_i) \quad (2)$$

where S and O are the simulated and observed data, and n is the number of observations.

Once the crop model was calibrated and validated, impact assessment in terms of crop yield and water requirements were calculated for the near future (2021–2050) and far future (2071–2100) in comparison to the baseline period (1981–2010), hereafter called NF, FF, and B, respectively. Then a set of autonomous adaptation strategies (i.e. farmers' adaptations; Garrido et al. 2011) were tested to avoid or reduce the negative biophysical impacts found. Adaptations were compared to un-adapted baseline and future projections in terms of crop yield and water requirements. The adaptations included earlier sowing dates, up to 60 d in advance, at 15 d intervals, and cultivar changes through the modification of cultivar phenology. This latter was implemented through the change of the CERES cultivar coefficients controlling the duration of grain-filling (P5) and the grain-filling growth rate (G3). The P5 coefficient was changed, seeking a longer but feasible grain-filling from 800 to 850 GDD, while the grain-filling rate was increased by modifying the G3 coefficient from 8 to 9 mg d^{-1}; the objective was to test changes within the scope of current breeding research. These adaptations were simulated individually and in combination.

Water requirements were evaluated in terms of crop evapotranspiration (ETc; mm) estimated by the CERES-Maize crop model. Equally, this model was used for the determination of irrigation requirements (IRR; mm), and water use efficiency in terms of water productivity (TWP; kg m^{-3}) and irrigation water productivity (IWP; kg m^{-3}).

2.4. Extreme events

Impacts of extreme T_{max} events on maize were quantified by the method of Teixeira et al. (2013). Briefly, this approach considers (1) critical and limiting temperatures, which are the thresholds above which yield damage increases until a limit when total production fails; these limits are set to 35 and 45°C, respectively; (2) calculation of the stress intensity index (f_{HS}, fractional) based on the T_{max} during the sensitive period to temperature (30 d centered in the mid-point of the reproductive phase); it represents the intensity and number of stress events that may affect the crop during flowering; the mentioned period is considered as the only one sensitive to heat stress; and (3) the production damage index, calculated from the simulated attainable yield normalized by the maximum value for each period and location (f_{dmgn}); this index quantifies the impact on yield.

Similar to previous modifications (Hawkins et al. 2013), 2 changes to the method were made: (1) the use of daily T_{max} during 30 d after silking instead of the daytime T_{day}, given that current cultivars are adapted to the high temperature regime of the study area; and (2) the use of potential yield data from the CERES-Maize simulations instead of attainable yield, as simulations without nitrogen and water stresses were considered.

Both f_{HS} and f_{dmgn} were calculated and evaluated for the 5 locations (Fig. 1) and for the 3 periods (B, NF, and FF), with and without adaptation strategies.

3. RESULTS

3.1. Crop model calibration and validation

The combination of cultivar-specific coefficients that present agronomic coherence and the lowest RMSE and MBE between observed and simulated silking dates and yield data for the HELEN cultivar was determined (Table 3). RMSE for the silking date simulation (expressed in days after sowing, DAS) was 3.1 and 5.6 d for calibration and validation, respectively, with MBE values equal to –1 and 3 d, respectively. RMSE errors for yield assessment were 344 and 1457 kg ha^{-1} for calibration and validation, respectively, and MBE errors were –138 and 224 kg ha^{-1}, respectively.

3.2. Evaluation under the present climate

The ENS-EOBS ensemble mean of climate variables for the grain-filling period (June–August) showed small biases related to measured data by RIA (Table 2); all locations showed a small bias or no difference with respect to the RIA dataset for monthly T_{max}, T_{min} (except for Granada), and precipitation (Table 2). Precipitation biases were not considered important in this study because crops were well irrigated.

The evaluation of ENS-EOBS was extended to its performance on impact assessment comparing yield simulations done by CERES-Maize with RIA and

Table 3. Cultivar-specific parameters calibrated in the CERES-Maize crop model for the HELEN cultivar (FAO 700) using measured data from Red Andaluza de Experimentación Agraria (RAEA) experiments. P1: thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant has no response to changes in photoperiod; P2: extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h); P5: thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8°C); G2: maximum possible number of kernels per plant; G3: kernel filling rate during the linear grain-filling stage and under optimum conditions (mg d^{-1}); PHINT: phylochron interval, the interval in growing degree days (GDD, °Cd) between successive leaf tip appearances

P1	P2	P5	G2	G3	PHINT
245	0	800	1100	8	45

Table 4. Simulated yield run with observed Agroclimatic Information Network of Andalusia (RIA) data (2001–2010), and interannual variability (coefficient of variation, CV_{time}). Difference (% of yield) regarding RIA-derived simulations and those conducted with the bias-corrected ensemble ENS-EOBS for the baseline period (1981–2010), and CV_{time} for these simulations

Location	Climate data used in the crop simulations			
	RIA		ENS-EOBS vs. RIA	
	Yield (kg ha^{-1})	CV_{time} (%)	Yield difference (%)	CV_{time} (%)
Alcalá del Río	16 177	8.7	1.9	7.3
Lora del Río	16 055	10.8	1.1	7.7
Palma del Río	16 094	10.8	0.6	7.4
Córdoba	15 961	7.5	1.0	7.7
Granada	16 966	4.5	–6.1	8.6

ENS-EOBS weather datasets for the baseline period (Table 4). The yield difference ranged from –6.1 % (for Granada) to 0.6 % (for Palma del Rio; Table 4). Both simulated time series showed similar interannual variability (coefficient of variation, CV_{time}), with the greatest difference in Granada (Table 4).

3.3. Impact and adaptation projections

Simulated phenological dates for Palma del Río (representative of Guadalquivir locations) and Granada are shown in Fig. 2 for B, NF, and FF periods. As GDD accumulated faster in future climate, both silking (anthesis date, ADAT) and maturity (MDAT) dates occurred earlier compared to the baseline simulations when sowing date was not changed, leading to a shorter grain-filling duration (MDAT – ADAT), especially in the FF period (ca. 17 d for the Guadalquivir locations and 20 d for Granada).

The simulated yield impact for irrigated maize, considering an optimal irrigation schedule for the ENS-EOBS ensemble mean, is shown in Table 5 for the B, NF, and FF periods and for the 5 locations. The results show a decrease in maize yield, greater in FF, when yield decrease was ca. 6–7 % at Guadalquivir locations and ca. 20 % in Granada. However, these effects when compared to the B period were only statistically significant in Córdoba and Granada (Table 5).

Interannual variability (CV_{time} in % for the 30 yr period) in the future (NF and FF) was ca. 8 % for all

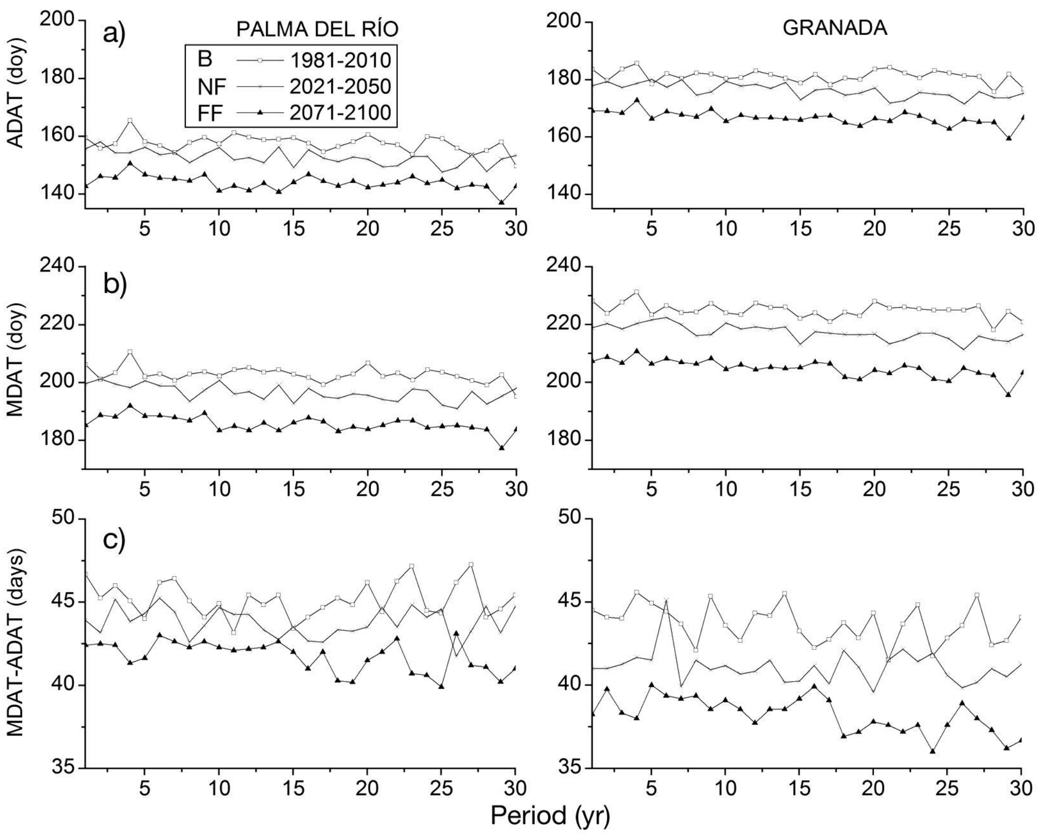

Fig. 2. Simulated phenology for the baseline period (1981–2010), near future (2021–2050), and far future (2071–2100): (a) anthesis date (ADAT), (b) maturity date (MDAT), and (c) grain-filling duration (MDAT – ADAT). doy: day of the year

Table 5. Simulated yield obtained with the bias-corrected ensemble ENS-EOBS. Difference (% of yield) between future and baseline periods is indicated in brackets. [a,b]Significant differences ($p < 0.05$). Interannual variability is expressed as coefficient of variation from year to year (CV_{time}); spread of the ENS-EOBS-derived ensemble of impacts is expressed as coefficient of variation among the 12 projections ($CV_{ensemble}$)

	Yield (kg ha^{-1})	CV_{time} (%)	$CV_{ensemble}$ (%)
B (1981–2010)			
Alcalá del Río	16 491^{a}	7.3	6.9
Lora del Río	16 238^{a}	7.7	7.0
Palma del Río	16 194^{a}	7.4	6.9
Córdoba	16 118^{a}	7.7	6.6
Granada	15 924^{a}	8.6	6.2
NF (2021–2050)			
Alcalá del Río	16 272^{a} (−1.3 %)	7.9	7.4
Lora del Río	16 016^{a} (−1.3 %)	7.9	7.0
Palma del Río	16 012^{a} (−1.1 %)	7.7	6.4
Córdoba	15 885^{ab} (−1.4 %)	7.7	6.3
Granada	15 061^{a} (−5.3 %)	9.2	4.4
FF (2071–2100)			
Alcalá del Río	15 410^{a} (−6.5 %)	8.0	6.9
Lora del Río	15 127^{a} (−6.8 %)	8.1	7.2
Palma del Río	15 126^{a} (−6.5 %)	8.1	7.0
Córdoba	15 006^{b} (−6.8 %)	8.5	6.9
Granada	12 665^{b} (−20.6 %)	15.0	12.3

Guadalquivir locations, similar to that of the baseline simulations (Table 5). Granada showed a higher increase in variability, especially in the FF (ca. 15 %). The spread or uncertainty related to the differences among the 12 RCM projections that form ENS-EOBS was measured by the coefficient of variation among them ($CV_{ensemble}$, %). This spread was similar for all locations ($CV_{ensemble}$: 7–8 %), decreasing slightly in the FF, except for Granada, where it increased up to ca. 12 % (Table 5).

These results show that recovering the baseline yields, particularly in Granada, requires adaptation measures. The first adaptation proposed consisted of earlier sowing dates (Fig. 3a,b).

Analyzing Fig. 3a, sowing dates 30 d earlier allowed for recovering the baseline yield in NF, although the option that minimized the impact was sowing 45 d earlier for all locations in FF (Fig. 3b). Results indicate a different behavior for Granada than for the rest of the locations. In Granada, even with earlier sowing dates, future yield was 9 to 11 % lower than that for the B period, while in the other locations, yield was consistently around 3 % lower than for the B period.

The second adaptation proposed in this study was the modification of the cultivar, adapting the grain-filling duration (P5 in Table 3) and grain-filling rate (G3 in Table 3) (Fig. 3c). For the NF period, modifying grain-filling duration was enough to recover the baseline yield (results not shown). However, for the FF period, baseline yields were recovered for all locations except for Granada, which still had lower yields than in the B period. Similar behaviour was found when grain-filling rate was increased. The combination of both changes in the cultivar exceeded the B yields by up to 10 % at all locations except Granada, where the yield remained ca. 10 % lower than that of the B simulations.

The advance in sowing dates and the changes in crop phenology were combined in several ways, to improve Granada's result, and to explore the potential of these combinations for the Guadalquivir locations (Fig. 3d for FF). When the sowing date was advanced by 30 d and the cultivar-specific coefficients were set to P5 = 850 GDD and G3 = 9 mg d^{-1}, the B yields were recovered at Granada (0.2 % of change). The same phenology, but with a sowing date 45 d earlier, showed an even higher yield for Granada (4.5 % of change). However, the 30 d option was the adaptation selected (hereafter called ADPS), valid for all locations to minimize disruption of the current cropping system, as large shifts in sowing dates may imply changes in crop rotations.

An average reduction of ETc of 10 and 25 % was found for the NF and FF, respectively (Table 6). The baseline ETc values were lower for Granada than for the Guadalquivir locations. IRR ranged from 668 mm for Granada to 726 mm for the Guadalquivir Valley. As a consequence of the ETc reductions, IRR showed decreases of around 9 % in all locations for the NF period, which were slightly higher for the Guadalquivir locations (ca. 25 %) compared to Granada (ca. 16 %) by the end of the 21st century. These reductions in ETc and IRR values were accompanied by an increase in water productivity (Table 6); both TWP and IWP were higher for all locations in NF and FF compared with baseline values.

In the ADPS simulations for Guadalquivir locations, ETc values increased around 3.5 % compared with the results obtained without adaptation strategies. This increase was around 9.5 % for Granada. The IRR results showed limited changes for the Guadalquivir locations (0.4 and −1.1 %) and an increase for Granada (7 and 6 %) for NF and FF periods, respectively, compared with the same periods

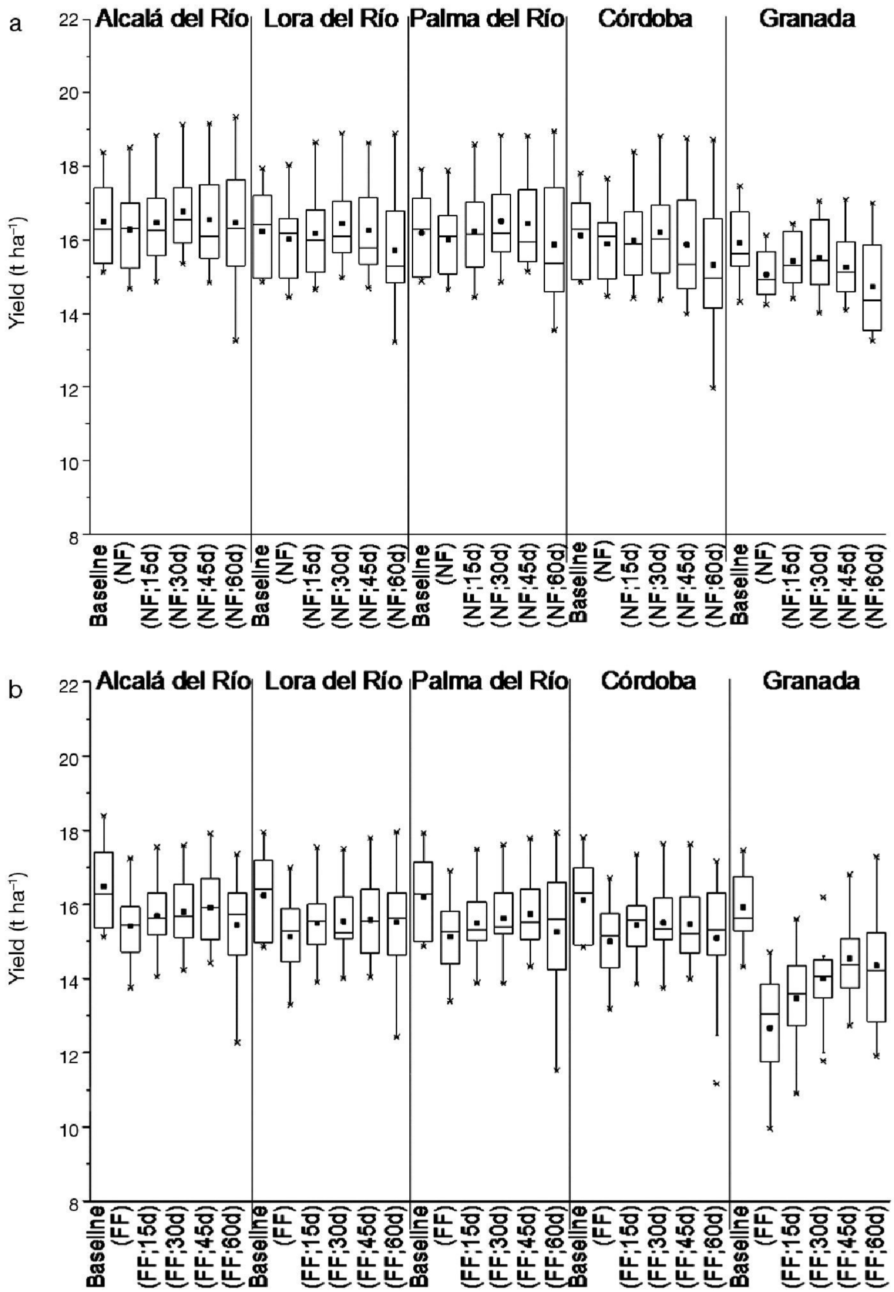

Fig. 3 (continued on next page). Projections of crop yield, impacts, and adaptations for the 12 regional climate model (RCM) projections of the bias-corrected ensemble ENS-EOBS at each location. The *y*-axis shows the simulated yield; *x*-axis specifies the simulation: yield for 1981–2010 (baseline), yield without adaptation for 2051–2071 or near future (NF), for 2071–2100 or far future (FF), and adaptations for NF (NF; adaptation) and FF (FF; adaptation). Adaptations are as follows: (a) sowing date advanced 15, 30, 45, and 60 d in the NF; (b) sowing date advanced 15, 30, 45, and 60 d in the FF; (c) increase in the CERES cultivar coefficients for duration of grain-filling (P5) and grain-filling rate (G3), and increase in both P5 and G3, in the FF; (d) combination of sowing 30 d earlier and increased P5, sowing 30 d earlier and increased G3, and sowing 30 d earlier and increased P5 and G3, in the FF. Boxplots show the distribution of the 12 RCM-derived results: box: 2nd and 3rd quartiles; line in the middle: median; point in the middle: mean; whiskers: maximum and minimum

without adaptation. Nevertheless, ETc and IRR values were still lower in NF and FF periods than for the B period for all locations when adaptation was simulated (Table 6). TWP and IWP values were higher with ADPS than without adaptations for the same periods.

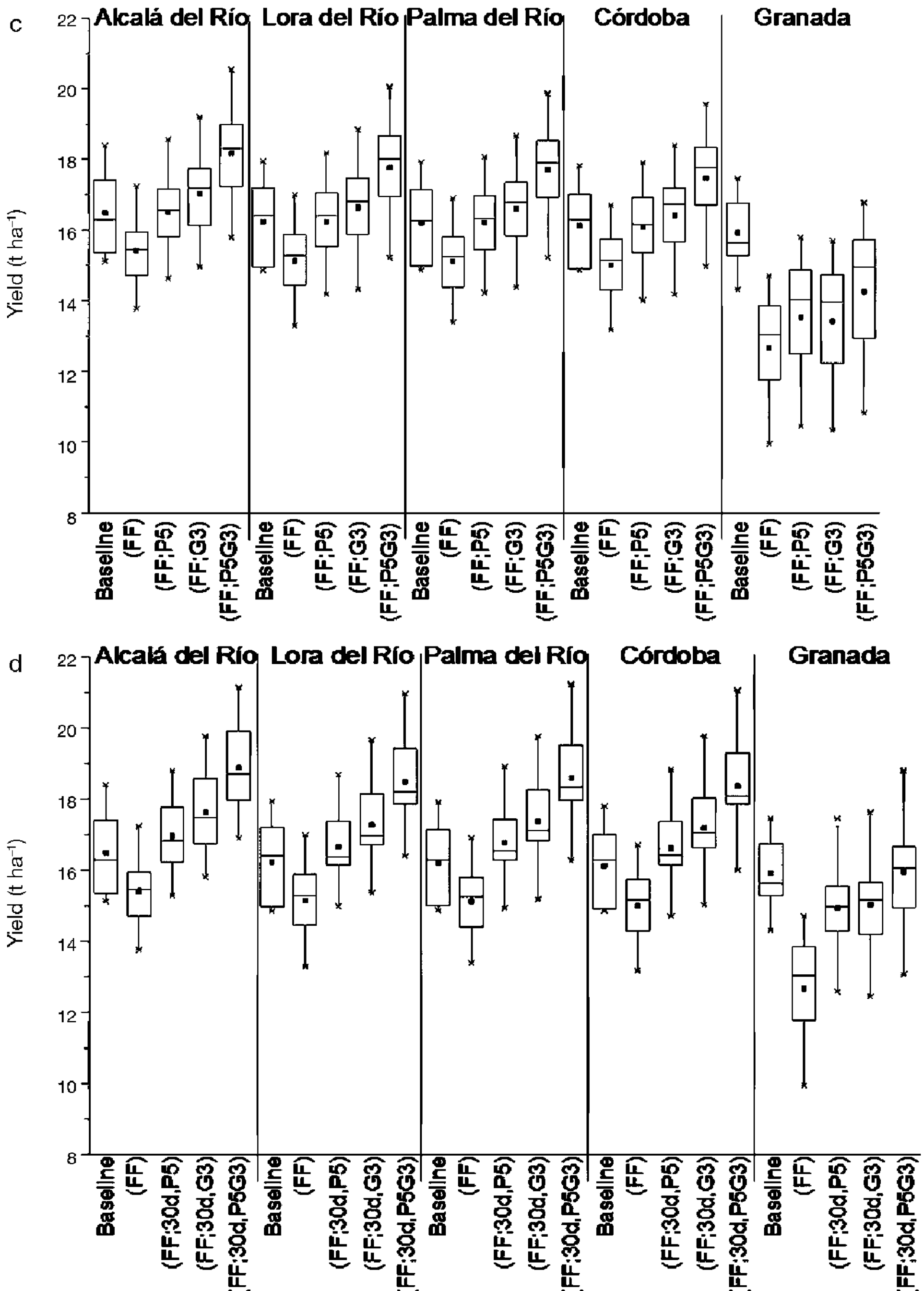

Fig. 3 (continued)

3.4. Extreme events

f_{HS} increased for all locations and for both NF and FF periods (Fig. 4). The increase for the future periods compared with the B period was lower in the Guadalquivir Valley locations than for Granada. The implementation of ADPS in NF resulted in a slight decrease of f_{HS} in the Guadalquivir locations, and in a minor increase in FF. In Granada, the compensation was lower, increasing in both NF and FF compared with the B period.

f_{dmgn} showed an increase in all locations for the future periods (Fig. 5), as expected due to the f_{HS} results. This increase was more evident in Granada than in the Guadalquivir locations at the end of the 21st century. This index was also evaluated with the

Table 6. Mean values of crop cycle duration, maturity date (MDAT), total season evapotranspiration (ETc), total irrigation requirements (IRR), water productivity (TWP), and irrigation water productivity (IWP), with the 12 regional climate models of the bias-corrected ensemble ENS-EOBS, for the baseline period (1981–2010), near future (2021–2050), and far future (2071–2100), with (ADPS) and without ('Impact') adaptation. ADPS: 30 d adaptation selected, doy: day of the year

		Crop cycle (d)	MDAT (doy)	ETc (mm)	IRR (mm)	TWP (kg m^{-3})	IWP (kg m^{-3})
Alcala del Río							
1981–2010	Baseline	138	200	722	729	3.1	2.3
2021–2050	Impact	132	194	650	659	3.5	2.5
	ADPS	154	187	673	658	4.2	3.1
2071–2100	Impact	121	183	543	554	4.1	2.8
	ADPS	143	175	555	543	4.9	3.5
Lora del Río							
1981–2010	Baseline	137	202	705	699	3.1	2.3
2021–2050	Impact	131	196	635	631	3.5	2.6
	ADPS	153	189	665	633	4.1	3.1
2071–2100	Impact	120	185	532	531	4	2.9
	ADPS	141	177	550	527	4.8	3.5
Palma del Río							
1981–2010	Baseline	137	203	730	768	3.1	2.1
2021–2050	Impact	130	196	658	697	3.5	2.3
	ADPS	154	190	682	697	4.2	2.9
2071–2100	Impact	121	186	555	592	4	2.6
	ADPS	143	179	566	580	4.9	3.2
Córdoba							
1981–2010	Baseline	138	204	713	710	3.1	2.3
2021–2050	Impact	131	197	643	645	3.5	2.5
	ADPS	154	191	673	653	4.1	3
2071–2100	Impact	121	187	539	542	4	2.8
	ADPS	143	180	562	544	4.8	3.4
Granada							
1981–2010	Baseline	126	225	688	668	3.2	2.4
2021–2050	Impact	119	217	623	608	3.4	2.5
	ADPS	142	211	684	649	3.9	2.8
2071–2100	Impact	108	205	525	527	3.4	2.5
	ADPS	129	198	575	560	4.1	2.9

ADPS adaptation for the future periods, compared with the B period without ADPS (Fig. 5), showing a decrease in production damage for NF at the Guadalquivir locations equal to 26%, and a slight increase in Granada (5%). This trend continued into the FF, with a decrease in production damage in the Guadalquivir locations of 8% and an increase in Granada (8%) compared to B.

The uncertainty of the f_{dmgn} projections was evaluated in terms of the ensemble spread: Granada showed the highest ensemble spread for the FF period, with differences between maximum and minimum f_{dmgn} values of 0.7, compared with 0.4 for the Guadalquivir locations. Equally, FF was the period with higher spread among the projections when adaptation was simulated, for all locations (Fig. 5).

4. DISCUSSION

4.1. Impacts

The model parameterization and the errors of model calibration and validation were similar to those determined in previous studies (Meza et al. 2008, Vučetić 2011, Angulo et al. 2013, Moradi et al. 2013).

Granada presented different results than the other locations. Granada station is not well represented by the E-OBS grid cell. The complex orography of the Granada area has a lower altitude (633 m), compared to the mean grid altitude of 1034 m for both E-OBS and ENS-EOBS. This could explain the higher bias in temperatures, which was not improved by bias correction. Also, this could explain why yield simulation

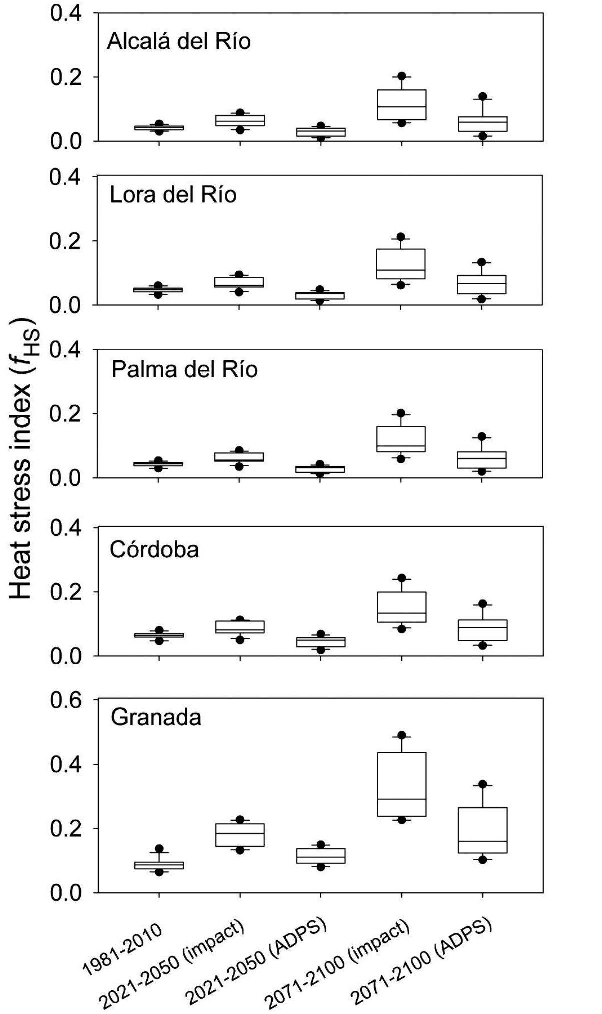

Fig. 4. Heat stress index (f_{HS}) for the baseline period (1981–2010), near future (2021–2050) without adaptation ('impact') and with the 30 d adaptation selected (ADPS), and for the far future (2071–2100) without adaptation ('impact') and with the ADPS. Lower part of the box: first quartile; line in the middle: median; upper part of the box: third quartile; vertical lines (whiskers): maximum and minimum; dots: outliers

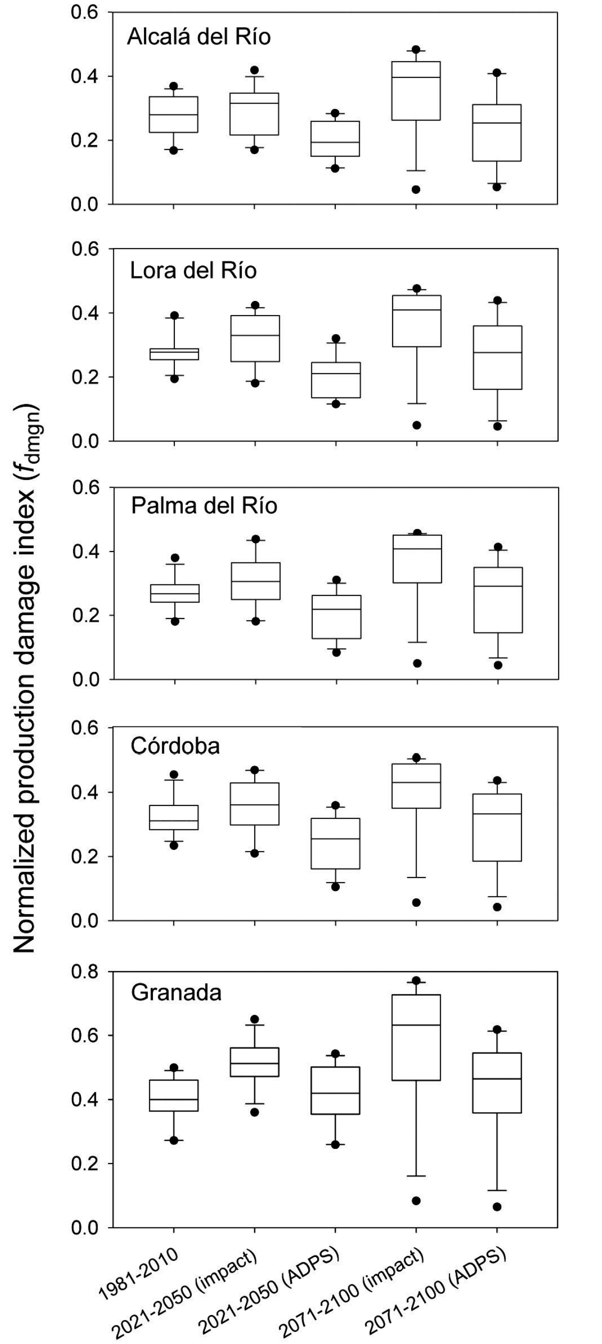

Fig. 5. Same as for Fig. 4, but for normalized yield damage index (f_{dmgn})

could not be improved and why there was high uncertainty of crop projections at Granada.

In the Guadalquivir locations, yield decrease in the FF period was moderate and smaller than indicated by previous projections for the Guadalquivir basin (Guereña et al. 2001, Garrido et al. 2011, Rey et al. 2011). However, yield impacts in Granada were in agreement with those previous studies. This response at Granada could be explained because the grain-filling duration projected for the FF period decreased more than at the other locations.

The overall uncertainty of these projections is low compared to other studies (Ruiz-Ramos & Mínguez 2010). This is a consequence of (1) conducting simulations under an optimum irrigation supply, excluding uncertainty linked to precipitation, which is usually high for the IP (Sánchez & Miguez-Macho 2010); and (2) the use of the bias-corrected ensemble ENS-OBS. Furthermore, the variability of climate conditions in the selected locations adds value to the study and increases the representativeness of the results.

4.2. Agronomic adaptations

Earlier sowing dates showed positive effects in agreement with previous studies (Tubiello et al. 2000, Moriondo et al. 2011). In Andalusia, the optimum sowing date is determined by matching the crop cycle to a period of temperatures warm enough to not limit maize growth, but cool enough to allow for a long crop cycle, and especially a long grain-filling period. Our results are relevant for adaptation studies, which usually use static sowing dates through the adaptation simulation for simplicity (e.g. Moriondo et al. 2011). A simple rule for computing the sowing date as a function of the year or decade could be more realistic and easy to implement.

Ideotypes taking advantage of the changed conditions with a longer and more efficient grain-filling period would be feasible, and breeders are currently investigating increasing leaf area duration (LAD), stay-green trait (Chen et al. 2013, Ning et al. 2013), and extending the duration of grain-filling (Tollenaar & Lee 2011). The 2 coefficients affecting the targeted variables were modified within a feasible range, taking as reference their values from previously calibrated cultivars. The simulations confirmed that these changes are promising, although in Granada, further adaptations would be needed.

The combination of both strategies confirms that their effects are not additive. The objective of recovering the potential baseline yield in Granada was accomplished with the combined adaptation ADPS. Future farming will exhibit a yield gap (Cassman et al. 2003, van Ittersum et al. 2013) compared to our simulations. The crop model does not simulate some processes, such as pests and diseases that could be enhanced by longer crop cycles, together with elevated temperatures. Also, the current model description of some processes might not be robust enough under future conditions (Prasad et al. 2006). Therefore, the actual yields should be lower than our projections (ca. 36%; see MAGRAMA 2013 for current yields).

For crop irrigation requirements (IRR), Mínguez et al. (2005) determined increases in crop water requirements; however, Yano et al. (2007) reported an IRR reduction of 25% in 2079 for Turkey, and Guereña et al. (2001) showed a reduction of 16% for maize in Spain in 2050, due to the CO_2 concentration increase. In our study, the observed decrease in estimated IRR for future periods without adaptation strategies agrees with these studies, and could be explained by: (1) reduction of the crop cycle duration due to warmer temperatures, avoiding the crop cycle going into the summer; and (2) the ETc reduction due to decreased stomatal conductance as an effect of future CO_2 concentrations (Cure & Acock 1986, Ainsworth & Long 2005).

IRR values under the ADPS simulations were lower for the NF and FF periods than for the B period. This reduction could be due to the earlier maturity dates, avoiding the driest and hottest period for the maize crop.

The increased water productivity (TWP) in the future periods could be related to reduced stomatal conductance (Leakey et al. 2006, Vanuytrecht et al. 2012). When the adaptations were implemented, TWP and IWP increased because yield increased more than crop transpiration and irrigation water requirements, respectively.

4.3. Extreme T_{max} events

In this study, we considered daily T_{max} instead daytime T_{day}: (1) to take into account that cultivars used in the Mediterranean region could have more heat tolerance than those of colder latitudes; and (2) to test another possible adaptation consisting of developing cultivars with further tolerance to high temperatures.

The increase in projected heat stress index resulted in an increase in production damages at the end of the 21st century, in agreement with previous results (Beniston et al. 2007, Ruiz-Ramos et al. 2011). The adaptation strategies tested here, such as the crop cycle change and the consideration of new cultivars, diminish negative impacts at field, regional, and European levels (Olesen et al. 2011). However, our results emphasize that the adaptations for these events must be local, due to differences in the spatial pattern of extreme events (Teixeira et al. 2013).

5. CONCLUSIONS

The CERES-Maize crop model was calibrated and validated using experimental data for 5 semi-arid locations, spanning an overall time period of 9 yr, obtaining a locally tailored approach for yield and irrigation needs estimation. Analysis of how extreme events can enhance or reduce the impacts, and the effect of adaptation strategies, is essential. The methodological improvement obtained with bias correction increased the quality of the climate data inputs.

A negative impact of climate change on irrigated maize yield was simulated due to (1) the reduction in ETc caused by the shorter crop cycle, and (2) an increase in the frequency of events generating heat stress. The implementation of adaptation strategies consisting of a combination of earlier sowing dates and cultivars with a more efficient grain-filling period could compensate both effects, and even increase the maize yield in southern Spain. In parallel, irrigation requirements were reduced around 25% for future periods compared with the baseline period, both with and without adaptation strategies, due to the reduction in ETc and higher water use efficiency.

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LITERATURE CITED

Ainsworth EA, Long SP (2005) What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. New Phytol 165:351–371

Angulo C, Rötter R, Lock R, Enders A, Fronzek S, Ewert F (2013) Implication of crop model calibration strategies for assessing regional impacts of climate change in Europe. Agric Meteorol 170:32–46

Beniston M (2004) The 2003 heat wave in Europe: a shape of things to come? An analysis based on Swiss climatological data and model simulations. Geophys Res Lett 31: L02202, doi:10.1029/2003GL018857

Beniston M, Stephenson DB, Christensen OB, Ferro CAT and others (2007) Future extreme events in European climate: an exploration of regional climate model projections. Clim Change 81:71–95

Bindi M, Olesen JE (2011) The responses of agriculture in Europe to climate change. Reg Environ Change 11: 151–158

Boote KJ, Jones JW, White JW, Asseng S, Lizaso JI (2013) Putting mechanisms into crop production models. Plant Cell Environ 36:1658–1672

CAP (Consejería de Agricultura y Pesca) (2011) Agenda del regadío andaluz. Horizonte 2015. CAP, Junta Andalucía, Seville (in Spanish)

Cassman KG, Dobermann A, Walters DT, Yang H (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. Annu Rev Environ Resour 28:315–358

Castro CL, Pielke RA Sr, Leoncini G (2005) Dynamical downscaling: assessment of value retained and added using the Regional Atmospheric Modeling System (RAMS). J Geophys Res Atmos 110:D05108, doi:10.1029/2004JD004721

Ceglar A, Kajfež-Bogataj L (2012) Simulation of maize yield in current and changed climatic conditions: addressing modelling uncertainties and the importance of bias correction in climate model simulations. Eur J Agron 37:83–95

Chen X, Chen F, Chen Y, Gao Q and others (2013) Modern maize hybrids in Northeast China exhibit increased yield potential and resource use efficiency despite adverse climate change. Glob Change Biol 19:923–936

Christensen JH, Christensen OB (2007) A summary of the PRUDENCE model projections of changes in European climate by the end of this century. Clim Change 81:7–30

Christensen JH, Rummukainen M, Lenderink G (2009) Formulation of very-high-resolution regional climate model ensembles for Europe. In: van der Linden P, Mitchell JFB (eds) ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project. UK Met Office Hadley Centre, Exeter, p 47–58

Christensen OB, Goodess CM, Ciscar JC (2012) Methodological framework of the PESETA project on the impacts of climate change in Europe. Clim Change 112:7–28

Cure JD, Acock B (1986) Crop responses to carbon dioxide doubling: a literature survey. Agric Meteorol 38:127–145

Dosio A, Paruolo P (2011) Bias correction of the ENSEMBLES high-resolution climate change projections for use by impact models: evaluation on the present climate. J Geophys Res Atmos 116:D16106, doi:10.1029/2011JD015934

Dosio A, Paruolo P, Rojas R (2012) Bias correction of the ENSEMBLES high resolution climate change projections for use by impact models : analysis of the climate changes signal. J Geophys Res Atmos 117:D17110, doi:10.1029/2012JD017968

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO (2000) Climate extremes: observations, modeling, and impacts. Science 289:2068–2074

Espadafor M, Lorite IJ, Gavilán P, Berengena J (2011) An analysis of the tendency of reference evapotranspiration estimates and other climate variables during the last 45 years in southern Spain. Agric Water Manage 98: 1045–1061

Essenwanger OM (2001) General climatology 1C: classification of climates. Elsevier, Amsterdam

Førland EJ, Benestad R, Hanssen-Bauer I, Haugen JE, Skaugen TE (2011) Temperature and precipitation development at Svalbard 1900–2100. Adv Meteorol 2011:893790, doi:10.1155/2011/893790

García-López J, Lorite IJ, García-Ruiz R, Domínguez J (2014) Evaluation of three simulation approaches for assessing yield of rainfed sunflower in a Mediterranean environment for climate change impact modelling. Clim Change 124:147–162

Garrido A, Rey D, Ruiz-Ramos M, Mínguez MI (2011) Climate change and crop adaptation in Spain: consistency of regional climate models. Clim Res 49:211–227

Gavilán P, Lorite IJ, Tornero S, Berengena J (2006) Regional calibration of Hargreaves equation for estimating reference ET in a semiarid environment. Agric Water Manage 81:257–281

Giannakopoulos C, Le Sager P, Bindi M, Moriondo M, Kostopoulou E, Goodess CM (2009) Climatic changes and associated impacts in the Mediterranean resulting from a 2°C global warming. Glob Planet Change 68: 209–224

Giorgi F, Hewitson B, Christensen J, Hulme M and others (2001) Regional climate information: evaluations and projections. In: Houghton JT, Ding Y, Griggs DJ, Noguer M and others (eds) Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press,

Cambridge, p 583–638
Gereña A, Ruiz-Ramos M, Díaz-Ambrona CH, Conde JR, Mínguez MI (2001) Assessment of climate change and agriculture in Spain using climate models. Agron J 93: 237–249
Hawkins E, Osborne TM, Ho CK, Challinor AJ (2013) Calibration and bias correction of climate projections for crop modelling: an idealised case study over Europe. Agric Meteorol 170:19–31
Haylock MR, Hofstra N, Tank AMGK, Klok EJ, Jones PD, New M (2008) A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. J Geophys Res Atmos 113:D20119, doi:10.1029/2008JD010201
Herrero MP, Johnson R (1980) High temperature stress and pollen viability of maize. Crop Sci 20:796–800
Hertig E, Seubert S, Jacobeit J (2010) Temperature extremes in the Mediterranean area: trends in the past and assessments for the future. Nat Hazards Earth Syst Sci 10: 2039–2050
Hoogenboom G, Tsuji G, Pickering N, Curry R, Jones J, Singh U, Godwin D (1995) Decision support system to study climate change impacts on crop production. In: Rosenzweig C, Allen LH Jr, Harper LA, Hollinger SE, Jones JW (eds) Climate change and agriculture: analysis of potential international impacts. Spec Publ 59. American Society of Agronomy, Madison, WI, p 51–75
Hoogenboom G, Jones JW, Wilkens PW, Porter CH and others (2010) Decision Support System for Agrotechnology Transfer (DSSAT) version 4.5. University of Hawaii, Honolulu
Iglesias A, Mínguez MI (1995) Perspectives for maize production in Spain under climate change. In: Rosenzweig C, Allen LH Jr, Harper LA, Hollinger SE, Jones JW (eds) Climate change and agriculture: analysis of potential international impacts. Spec Publ 59. American Society of Agronomy, Madison, WI, p 259–273
Jones C, Kiniry J (1986) CERES-Maize. A simulation model of maize growth and development. Texas A&M University Press, College Station, TX
Jones JW, Hoogenboom G, Porter CH, Boote KJ and others (2003) The DSSAT cropping system model. Eur J Agron 18:235–265
Kimball BA (1983) Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. Agron J 75:779–788
Kiniry JR (1991) Maize phasic development. In: Hanks J, Ritchie JT (eds) Modeling plant and soil systems. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI, p 55–70
Leakey ADB, Uribelarrea M, Ainsworth EA, Naidu SL, Rogers A, Ort DR, Long SP (2006) Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. Plant Physiol 140:779–790
López de la Franca N, Sánchez E, Domínguez M (2013) Changes in the onset and length of seasons from an ensemble of regional climate models over Spain for future climate conditions. Theor Appl Climatol 114:635–642
MAGRAMA (Ministerio de Agricultura, Alimentación y Medio Ambiente) (2013) Anuario de estadística, 2012. MAGRAMA, Madrid
MAGRAMA (Ministerio de Agricultura, Alimentación y Medio Ambiente) (2015) Análisis y prospectiva en medio ambiente, agricultura, pesca, alimentación y desarrollo rural. Dossier Autonómico Comunidad Autónoma Andalucía. MAGRAMA, Madrid. www.magrama.gob.es/es/ministerio/servicios/analisis-y-prospectiva/Dossier_Andalucia_tcm7-183042.pdf (accessed 19 Mar 2015)
Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305:994–997
Meza FJ, Silva D, Vigil H (2008) Climate change impacts on irrigated maize in Mediterranean climates: evaluation of double cropping as an emerging adaptation alternative. Agric Syst 98:21–30
Mínguez I, Ruiz A, Estrada A (2005) Impacts on the agrarian sector. A preliminary general assessment of the impacts in Spain due to the effects of climate change. Ministerio de Medio Ambiente, Madrid
Mínguez MI, Ruiz-Ramos M, Díaz-Ambrona CH, Quemada M, Sau F (2007) First-order impacts on winter and summer crops assessed with various high-resolution climate models in the Iberian Peninsula. Clim Change 81: 343–355
Moradi R, Koocheki A, Nassiri Mahallati M, Mansoori H (2013) Adaptation strategies for maize cultivation under climate change in Iran: irrigation and planting date management. Mitig Adapt Strateg Glob Change 18: 265–284
Moriondo M, Bindi M, Kundzewicz ZW, Szwed M and others (2010) Impact and adaptation opportunities for European agriculture in response to climatic change and variability. Mitig Adapt Strateg Glob Change 15:657–679
Moriondo M, Giannakopoulos C, Bindi M (2011) Climate change impact assessment: the role of climate extremes in crop yield simulation. Clim Change 104:679–701
Ning P, Li S, Yu P, Zhang Y, Li C (2013) Post-silking accumulation and partitioning of dry matter, nitrogen, phosphorus and potassium in maize varieties differing in leaf longevity. Field Crops Res 144:19–27
Olesen JE, Bindi M (2002) Consequences of climate change for European agricultural productivity, land use and policy. Eur J Agron 16:239–262
Olesen JE, Carter TR, Díaz-Ambrona CH, Fronzek S and others (2007) Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. Clim Change 81:123–143
Olesen JE, Trnka M, Kersebaum KC, Skjelvåg O and others (2011) Impacts and adaptation of European crop production systems to climate change. Eur J Agron 34:96–112
Osborne T, Rose G, Wheeler T (2013) Variation in the global-scale impacts of climate change on crop productivity due to climate model uncertainty and adaptation. Agric Meteorol 170:183–194
Palosuo T, Kersebaum KC, Angulo C, Hlavinka P and others (2011) Simulation of winter wheat yield and its variability in different climates of Europe: a comparison of eight crop growth models. Eur J Agron 35:103–114
Prasad PVV, Boote KJ, Allen LH (2006) Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [*Sorghum bicolor* (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. Agric Meteorol 139: 237–251
RAEA (Red Andaluza de Experimentación Agraria) (2012) Variedades comerciales de maíz. RAEA, Junta Andalucía, Seville
Rey D, Garrido A, Mínguez MI, Ruiz-Ramos M (2011) Impact

of climate change on maize's water needs, yields and profitability under various water prices in Spain. Span J Agric Res 9:1047–1058
Rötter RP, Carter TR, Olesen JE, Porter JR (2011) Crop–climate models need an overhaul. Nat Clim Change 1: 175–177
Ruiz-Ramos M, Mínguez MI (2010) Evaluating uncertainty in climate change impacts on crop productivity in the Iberian Peninsula. Clim Res 44:69–82
Ruiz-Ramos M, Sánchez E, Galllardo C, Mínguez MI (2011) Impacts of projected maximum temperature extremes for C21 by an ensemble of regional climate models on cereal cropping systems in the Iberian Peninsula. Nat Hazards Earth Syst Sci 11:3275–3291
Sánchez E, Miguez-Macho G (2010) Regional climate projections over the Iberian Peninsula: climate change scenarios modeling. In: Pérez F, Boscolo R (eds) Climate in Spain: past, present and future. Regional climate change assessment report. Clivar-Spain, Madrid, p 69–80
Sánchez E, Gallardo C, Gaertner MA, Arribas A, Castro M (2004) Future climate extreme events in the Mediterranean simulated by a regional climate model: a first approach. Glob Planet Change 44:163–180
Schär C, Jendritzky G (2004) Hot news from summer 2003. Nature 432:559–560
Semenov MA, Stratonovitch P (2010) Use of multi-model ensembles from global climate models for assessment of climate change impacts. Clim Res 41:1–14
Soil Survey Staff (1999) Soil taxonomy. Agric Handb 436, 2nd edn. Natural Resources Conservation Service, US Department of Agriculture, Washington, DC
Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA (2006) Going to the extremes. An intercomparison of model-simulated historical and future changes in extreme events. Clim Change 79:185–211
Teixeira EI, Fischer G, van Velthuizen H, Walter C, Ewert F (2013) Global hot-spots of heat stress on agricultural crops due to climate change. Agric Meteorol 170:206–215
Tollenaar M, Lee EA (2011) 2. Strategies for enhancing grain yield in maize. Plant Breed Rev 34:37–82
Travis WR, Huisenga MT (2013) The effect of rate of change, variability, and extreme events on the pace of adaptation to a changing climate. Clim Change 121:209–222
Trnka M, Rötter RP, Ruiz-Ramos M, Kersebaum KC, Olesen JE, Žalud Z, Semenov MA (2014) Adverse weather conditions for European wheat production will become more frequent with climate change. Nat Clim Change 4: 637–643
Tubiello FN, Donatelli M, Rosenzweig C, Stockle CO (2000) Effects of climate change and elevated CO_2 on cropping systems: model predictions at two Italian locations. Eur J Agron 13:179–189
van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z (2013) Yield gap analysis with local to global relevance—a review. Field Crops Res 143:4–17
Vanuytrecht E, Raes D, Willems P, Geerts S (2012) Quantifying field-scale effects of elevated carbon dioxide concentration on crops. Clim Res 54:35–47
Vučetić V (2011) Modelling of maize production in Croatia: present and future climate. J Agric Sci 149:145–157
Wilby RL, Wigley TML, Conway D, Jones PD, Hewitson BC, Main J, Wilks DS (1998) Statistical downscaling of general circulation model output: a comparison of methods. Water Resour Res 34:2995–3008
Yano T, Aydin M, Haraguchi T (2007) Impact of climate change on irrigation demand and crop growth in a Mediterranean environment of Turkey. Sensors (Basel) 7: 2297–2315